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Variation of phytoplankton absorption coefficients in the northern South China Sea during spring and autumn

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Abstract

We examined the temporal and spatial variabilities of phytoplankton absorption coefficients ($\alpha_{ph}(\lambda)$) and their relationships with physical processes in the northern South China Sea from two cruise surveys during spring (May 2001) and late autumn (November 2002). A large river plume induced by heavy precipitation in May stimulated a phytoplankton bloom on the inner shelf, causing significant changes in the surface water in α_{ph} values and B/R ratios ($\alpha_{ph}(440)/\alpha_{ph}(675)$). This was consistent with the observed one order of magnitude elevation of chlorophyll α and a shift from a pico/nano dominated phytoplankton community to one dominated by micro-algae. At the seasonal level, enhanced vertical mixing due to strengthened northeast monsoon in November has been observed to result in higher surface $\alpha_{ph}(675)$ (0.002–0.006 m^{-1} higher) and less pronounced subsurface maximum on the outer shelf/slope in November as compared that in May. Measurements of α_{ph} and B/R ratios from three transects in November revealed a highest surface $\alpha_{ph}(675)$ immediately outside the mouth of the Pearl River Estuary, whereas lower $\alpha_{ph}(675)$ and higher B/R ratios were featured in the outer shelf/slope waters, demonstrating the respective influence of the Pearl River plume and the oligotrophic nature of South China Sea water. The difference in spectral shapes of phytoplankton absorption (measured by B/R ratios and bathochromic shifts) on these three transects infers that picoprocaryotes are the major component of the phytoplankton community on the outer shelf/slope rather than on the inner shelf. In addition, a regional tuning of the phytoplankton absorption spectral model (Carder et al., 1999) demonstrated a greater spatial variation than seasonal variation in the lead parameter a0(λ). These results suggest that phytoplankton absorption properties in a coastal region such as the northern South China Sea are complex and region-based parameterization is mandatory in order for remote sensing algorithms.

1 Introduction

The absorption and scattering coefficients of various water constituents determine the optical properties in the ocean (Preisendorfer, 1961). Among them, phytoplankton absorption coefficient (α_{ph}) is a critical component. Characterization of α_{ph} and its chlorophyll-specific counterpart (α^*_{ph}), as well as their sources and scales of variability, is important for a variety of applications such as remote sensing of chlorophyll α (chlα) concentration and primary production (e.g. Bidigare et al., 1987; Morel et al., 1996; Carder et al., 1999).

A general trend in oceanic waters is that α_{ph} at a specific wavelength (e.g. 440, 675 nm) is well correlated with chlorophyll α concentration (chlα), a major pigment in algal cells, while random variation occurs in different regimes (Prieur and Sathyendranath, 1981; Carder et al., 1999; Cleveland, 1995; Lutz et al., 1996). A recent study in European coastal water revealed that the relationship between α_{ph} and chlorophyll concentration was overall similar to that previously established for open oceanic waters, although deviation occurred due to peculiar pigment composition and cell size (Babin et al., 2003). Similar results were also obtained in the Pearl River Estuary and the adjacent northeastern South China Sea (Cao et al., 2003; Xu et al., 2004). These studies generally support that α_{ph} should be a good indicator for changes of chl α and would be tightly associated with different water masses and physical dynamics.

Differences in phytoplankton absorption properties observed between and within species grown under various environmental conditions are ultimately governed by pigment composition and pigment package effects (Mitchell and Kiefer, 1988; Stramski and Morel, 1990; Sosik and Mitchell, 1991; Stuart et al., 1998; Lohrenz et al., 2003). For example, picoprokaryotes (cyanobacteria and marine prochlorophytes), the smallest phytoplankton group abundant in open ocean waters, were observed to have high α^*_{ph} (chlorophyll α-specific absorption coefficient of phytoplankton) at 440 nm and blue/red (B/R) ratios due to their small cell size and the high zeaxanthin or divinyl chl b concentration (Kana et al., 1988; Moore et al., 1995). Divinyl chl α/b contained

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in marine prochlorophytes show a ca. 8 nm bathochromic shift of absorption maximum compared to the normal chl a/b (Chisholm et al., 1988). Thus, variation of a_{ph} may be reflective of the variation in chl a as well as the phytoplankton community structure, which suggests an alternative optical approach to phytoplankton study especially when HPLC (high performance liquid chromatography) or flow cytometry data are not available (Moore et al., 1995). Most importantly, since a_{ph} can be remotely estimated, its potential application should be powerful.

Algorithms to retrieve absorption coefficients remotely, from empirical to full-spectral optimization, have as matter of fact been underway (e.g. Lee et al., 1998; Carder et al., 1999; Lee et al., 2002). Note that the retrieval accuracy of semi-analytical algorithms is often better than that of empirical algorithms (Bukata et al., 1995; IOCCG, 2000). However, the performance of these algorithms relies on accurate parameterization in the spectral models for the absorption coefficients of phytoplankton pigments and other light absorbing constituents. The spectral models for phytoplankton absorption are subject to spatial and temporal variation due to changing pigment composition and package effect. As a consequence, regional in situ studies on the variability of phytoplankton absorption properties are fundamental in order to parameterize the spectral models towards algorithms for remote sensing applications.

The South China Sea (SCS) is one of the major marginal seas. The Pearl River discharges into its northeast, through which the SCS receives freshwater as well as nutrients and pollutants from one of the most industrialized regions of China. Climatic variations in the atmosphere and the upper ocean of the SCS are primarily controlled by the East Asian monsoon, which follows closely the variations in the equatorial Pacific (Liu et al., 2002). Although it is basically an important low latitude marginal sea, its biogeochemistry has received relatively little attention. Recent arguments emerged towards a role of CO_2 source the SCS played (Zhai et al., 2005; Cai and Dai, 2004). Spatial and temporal patterns of phytoplankton are thus essential to understand the carbonate system. However, knowledge on phytoplankton, including chl a, taxonomy, primary production and the optical properties, is extremely limited, especially in the northern SCS (NSCS) adjacent to the Pearl River Estuary (PRE). There are a couple of reports found but the spatial and temporal changes are rarely discussed (Huang et al., 2002; Cao et al., 2003, 2005; Ning et al., 2003, 2004; Zhu et al., 2003; Xu et al., 2004; Lee Chen, 2005; Wang et al., 2005; Chen et al, 2006).

We obtained α_{ph} data during two cruises to the Northern South China Sea in May 2001 and November 2002. With the absence of pigment and taxonomic data, this paper attempts to apply α_{ph} as an alternative parameter for chl α and taxonomy and thus aims to examine the variation of phytoplankton absorption coefficients associated with hydrodynamics, in particular the changes in response to a plume event, and changes between a southwest monsoon season (late spring) and a northeast monsoon season (late autumn). Change of the α_{ph} spectral model parameterization is also examined to provide essential information for local semi-analytical remote sensing algorithm.

2 Methods

The NSCS was surveyed during two cruises (14 to 25 May 2001 and 2 to 21 November 2002) on board R/V Yanping II. Figure 1 shows the stations for CTD surveys and absorption sampling. The 2001 cruise involved one transect (Transect A, hereafter T-A), starting from the vicinity of the PRE to the southeast to Dongsha island, and crossing the shelf to the slope. The 2002 cruise had two more transects: Transect B (hereafter T-B) parallel to and to the east of T-A, and Transect C (hereafter T-C) located outside the PRE, along the coast. Following Zhai et al. (2005), T-A can be divided into two zones, inner shelf with water depths shallower than 100 m and within a range of ca. 75–130 km from the coast (Stas. 6C, 6 and 5A); and outer shelf/slope with water depths of 100–1000 m (Stas. 5, 4A, 2, 4, 3 and 3A).

Our May 2001 cruise was divided into two legs. The first cruise leg was between 14–19 May, and the second was during 24–25May. Stations 6 and 2 were sampled in both cruise legs for absorption coefficients (the second sampling is annotated as Sta. 6' and Sta. 2', respectively).

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Our sample collection and measurements strictly followed the Ocean Optics Protocols Version 2.0, distributed by NASA (Mitchell et al., 2000). Briefly, water samples were collected with 1.7 L Niskin bottles mounted on a rosette equipped with a SBE19 CTD which provides temperature and salinity data. Samples were then filtered onto a 25-mm 0.7 μm glass fiber filter (Whatman GF/F) under low vacuum (<17 kPa). Sample filters were put into tissue capsules (Fisher Histoprep^{TM}) and then stored in liquid nitrogen for subsequent laboratory analysis at Xiamen University.

Absorption was measured on a dual-beam Varian Cary-100 spectrophotometer loaded with an integrating sphere. Sample filters were first scanned from 250 to 800 nm relative to a blank filter saturated with 0.2 μm filtered seawater to obtain the total particulate absorbance spectra (OD_p). After pigment extraction with methanol, sample filters were measured again to obtain the absorbance spectra of the nonalgal particles (OD_d). $OD_p(440)$ and $OD_d(440)$ were all less than 0.4 absorbance.

Absorption coefficients of total particles (α_p) and nonalgal particles (α_d) were calculated as:

$$\alpha(\lambda) = 2.303 \times [\mathrm{OD}(\lambda) - \mathrm{OD_{null}}] \times \frac{A}{V\beta},$$

where A is the area of the sample filter with concentrated particles, V is the volume of water filtered and β is a parameter to correct for the pathlength amplification effect due to multiple scattering. A widely accepted β expression given by Cleveland and Weidemann (1993) was used for correction. OD_{null} is the average of the OD between 790 and 800 nm since it had been found that all aquatic particles generally show negligible absorption in the near infrared. Phytoplankton absorption coefficients (α_{ph}) were then calculated as the difference between α_p and α_d.

The absorption of water samples from depths >150 m was too weak to detect, and so only data for the upper 150 m of water are presented.

3 Results and discussion

3.1 Variations of a_{ph} magnitude and spectral shapes

3.2 Short term variation in May 2001

The outburst of SCS summer monsoon normally occurs in mid-May, leading to a rainy season (Qian et al., 2002). This was also the case in May 2001. Heavy precipitation appeared on 1 May, 7–9 May, 17–18 May, and 21–22 May, recorded at both Baiyun (Guangzhou) and Hong Kong weather observatories as described in a parallel study (Dai et al., 2007). Accumulation of this precipitation caused a river plume extending to the region near Sta. 6 as evidenced by low salinity between 24 to 25 May (Fig. 2). Surface water salinity sharply dropped from 34.0 to ~26.5 at Sta. 6. The plume, which apparently diminished at Sta. 5A, brought a significant amount of nutrients into the region shoreward of Sta. 5A, resulting in a phytoplankton bloom, as revealed by a parallel study on the carbonate system in this region (Dai et al., 2007).

Correspondingly, the absorption properties experienced significant changes during this period of observation. Figure 3 shows vertical profiles of $a_{ph}(675)$ observed on T-A in May 2001. During the first cruise leg between 15 and 19 May, the surface $a_{ph}(675)$ varied from 0.002 m^{-1} at Sta. 6 to 0.004 m^{-1} at Sta. 5A (~37 km apart) on the inner shelf, and no significant changes were found between the inner shelf and the outer shelf/slope. A subsurface maximum in $a_{ph}(675)$ existed both on the inner shelf and the outer shelf/slope, with value varying between 0.015–0.019 m^{-1}. During the second cruise leg between 24–25 May, however, the horizontal gradient of $a_{ph}(675)$ increased substantially. On the inner shelf, the surface $a_{ph}(675)$ became one order of magnitude higher than that on the outer shelf/slope. $a_{ph}(675)$ as high as 0.050 m^{-1} occurred at Sta. 6. This was equivalent to an increase of chl a from 0.1 to 2.6 mg m^{-3} using the model of Carder et al. (1999) ([chl a] $=56.8\times[a_{ph}(675)]^{1.03}$), which was consistent with the observed one order of magnitude elevation of chl a as reported by Dai et al. (2007).

The occurrence of a phytoplankton bloom around Sta. 6 was thus evident. In contrast, the outer shelf/slope maintained a low surface $a_{ph}(675)$ around $0.002\,m^{-1}$ and a subsurface/deep maximum varying between $0.005–0.014\,m^{-1}$. For the two stations we revisited, significant changes were solely found at Sta. 6, where surface $a_{ph}(675)$ increased from 0.002 to $0.050\,m^{-1}$.

B/R ratios on the inner shelf also showed significant changes (Table 1). During the first cruise leg, the surface B/R ratios, both on the inner shelf and on the outer shelf/slope, were greater than 3.0. This implies the predominance of picoprocaryotes in the phytoplankton community (Stramski and Morel, 1990; Partensky et al., 1993; Moore et al., 1995). However, during the second leg, surface B/R ratio at Sta. 6 dropped from 3.9 to 2.5, suggesting a decrease in the proportion of picoprocaryotes in the phytoplankton community. This can be confirmed by the finding in the parallel carbonate system study, which demonstrated that the phytoplankton community structure in terms of size-fractionated chl *a* significantly shifted from a pico/nano-phytoplankton dominated community to a structure dominated by micro-algae in surface water at Sta. 6 during the second cruise leg (Dai et al., 2007). Moreover, the shape of the a_{ph} spectrum changed substantially (Fig. 4). Strong absorptions were found at 636 and 485 nm, suggesting abundance of chl *c* and fucoxanthin, typically contained in diatoms (Bidigare et al., 1990). The absorption maximum in the blue region shifted from 440 to 432 and 410 nm, indicating increasing levels of phaeopigments (Lorenzen and Downs, 1986). It is thus suggestible that a diatom bloom at its late stage occurred around Sta. 6 when the second cruise leg took place. It should be noted that similar features in the a_{ph} spectra were observed at Sta. 6C (shoreward of Sta. 6, Fig. 4) with a B/R ratio as low as 2.1. On the outer shelf/slope, however, B/R ratios remained greater than 3.0 throughout the cruise.

3.2.1 Seasonal variation in the outer shelf on Transect A

The inner shelf water on T-A was clearly subject to significant short term variations in May (a high flow season of the PRE). Comparisons of α_{ph} between May and November, southwest and northeast monsoon seasons, will thus focus on the outer shelf/slope of T-A.

On average, the transition from the northeast to southwest monsoon in the SCS occurs in May and that from the southwest to the northeast occurs in October (Lau et al., 1998). Figure 5 displays the monthly mean distribution of QuikSCAT wind stress in the region under study in May 2001 and November 2002. The maximum northeasterly wind stress in November 2002 could be up to 0.25 N m^{-2}. The wind stress in May 2001 was much smaller (mostly <0.1 N m^{-2}) and variable in direction. The effect of wind forcing superimposed on surface cooling convective overturn in the northeast monsoon season would lead to enhanced vertical mixing, resulting in a deepening of mixed layer depth (MLD). Deepening of MLD in the region of interest in November 2002 as compared to May 2001 was obvious (Fig. 6). Except for Sta. 5, which was located at 100 m isobath, MLD on the outer shelf/slope of T-A varied between 60–100 m in November, while it was less than 20 m in May. This suggests that the nutrients in the upper nutricline are more readily for primary production, leading to elevated chl a and primary productivity, as had observed at a SCS time series station (SEATS) located in the NSCS (Tseng et al., 2005).

Concomitantly, both the surface value and the vertical structure of $\alpha_{ph}(675)$ on the outer shelf/ slope of T-A in November 2002 differed from that in May 2001 (Fig. 7). For example, surface $\alpha_{ph}(675)$ along T-A varied from 0.005 to 0.009 m^{-1} in November, higher by 0.002–0.006 m^{-1} than those observed at the same stations in May 2001. Although subsurface maxima also existed in November, they were far less prominent than those in May. The differences between the subsurface maxima and the surface values were typically less than 0.003 m^{-1} in November for most stations, whereas in May they were higher by at least a factor of two as compared to the November values.

On the outer shelf of T-A, B/R ratios were generally greater than 3.0 in the upper water in both seasons, although the values were slightly higher in May than in November (Table 2). Below the surface, B/R ratios at most of the sampling stations were less than 2.5 in November but greater than 2.5 in May. Difference between these two seasons may be primarily a result of photoacclimation since higher light condition is usually observed in May.

3.2.2 Spatial variation in November 2002

The survey of November 2002 covered a broader regions, T-B and T-C, in addition to T-A. Figure 8 displays their different hydrological properties. T-C was within ~50 km distance from the coast, highly impacted by YueDong Coastal Water. This water mass, low in salinity, is rich in nutrients and thus maintains a relatively high level of chl α and primary productivity (Li and Su, 2001). T-B and T-A were on the shelf. T-B was located east of the PRE. Since the Pearl River plume went southwestward under the forcing of the northeast monsoon in November (Su, 2004), T-B was beyond the impact of the Pearl River plume. T-A, on the contrary, was right outside the PRE. Nutrient loadings from the river plume to T-A was thus expected. On the other hand, it was suggested that vertical turbulence might have been reinforced on T-A due to the input of the Pearl River plume (Mann and Lazier, 1996), leading to a deeper MLD on T-A than on T-B (Fig. 8). This implies that nutrients might be more available for phytoplankton growth in the upper layer on T-A.

Corresponding to the different physical regimes, a clear spatial pattern of $\alpha_{ph}(675)$ appeared. As Fig. 9 shows, surface $\alpha_{ph}(675)$ was much higher on T-C than that on T-A and T-B. It ranged between 0.010–0.018 m^{-1} on T-C, corresponding to a range of chl α between 0.49–0.91 mg m^{-3} according to the algorithm of Carder et al. (1999). The highest value occurred at Sta. C4, which was located facing and closest to the PRE, demonstrating that the Pearl River plume in this low flow season could still be influential to the area around 21.8° N (see Fig. 1 for the location). There was no distinct subsurface/deep maximum in $\alpha_{ph}(675)$ on T-C, although $\alpha_{ph}(675)$ was slightly higher in deeper water than at the surface.

Surface $\alpha_{ph}(675)$ of T-B was relatively low compared to that of T-A, either on the inner shelf or on the outer shelf/slope. It was nearly homogenous, staying around $0.005\,m^{-1}$ over the entire T-B. In contrast, it had a greater horizontal gradient along T-A, varying between a minimum of $0.005\,m^{-1}$ on the outer shelf/slope and a maximum of $0.015\,m^{-1}$ on the inner shelf. Vertical structures of $\alpha_{ph}(675)$ were also different. A prominent subsurface $\alpha_{ph}(675)$ maximum was present on T-B, with a maximum level of $0.021\,m^{-1}$, especially on the outer shelf/slope. For T-A, although a subsurface $\alpha_{ph}(675)$ maximum was visible, the values were lower. These variations of $\alpha_{ph}(675)$ between two shelf transects, T-A and T-B, partly proved that the Pearl River plume affected the inner shelf of T-A by supplying more nutrients for phytoplankton growth, either through direct input or by enhancing vertical mixing.

B/R ratios also changed among the three transects (Table 1). Generally, T-C had the lowest value (<2.5 for most stations) and T-B had the highest (>2.5 for most stations) (Table 1). On T-A, B/R ratios were higher on the outer shelf/slope than on the inner shelf, especially surface B/R ratios were close to or greater than 3.0 on the outer shelf/slope. Typical eukaryotic phytoplankton studied in the laboratory has not been observed with peak B/R ratios in excess of 2.5 (Cleveland et al., 1989), while picoprokaryotes can exhibit B/R ratios much greater than that (Stramski and Morel, 1990; Partensky et al., 1993; Moore et al., 1995). It seems that picoprocaryotes dominated on T-B and the outer shelf/slope of T-A, while this was not the case for T-C and the inner shelf of T-A, where the impact of Pearl River plume and coastal water might be severe. Another evidence was bathochromic shifts phenomena especially for *Prochlorococcus*. Bathochromic shifts from 440 nm were observed in the entire water column of T-B and on the outer shelf of T-A in November (Fig. 10a). Such a shift increased in intensity from 4–6 nm to 40 nm in the deeper water while approaching the slope (Fig. 10b). Bathochromic shifts of ~7 nm, consistent with the presence of *Prochlorococcus*, were found in the deep layer of the Sargasso Sea (Bricaud and Stramski, 1990). A similarly strong shift of ~40 nm has been observed in the tropical North Atlantic (Lazzara et al., 1996). The shifts we encountered in November strongly suggested the presence of *Prochlorococcus* in this season. This is partly supported by a parallel study on phytoplankton community structure on T-A based on HPLC pigment analysis (Chen et al., 2006). It was revealed that diatom dominated in the Pearl River Estuary and the adjacent coastal area. However, the proportion of Prymnesiophyta, cyanobacteria and *Prochlorococcus* were main groups in the offshore water. The contribution of cyanobacteria and *Prochlorococcus* to chl a was 16–33% and 14–26% respectively on the outer shelf (Sta. 5 was marked as SCS04 in Chen et al., 2006).

3.3 Variations in the absorption spectral model parameters

Among the SEADAS list of MODIS Level 3 products, there are absorption and backscatter coefficients derived from Carder et al. (1999) and QAA (Lee et al., 2002). Carder et al. (1999) chose a hyperbolic tangent function to model the relationship between $a_{ph}(\lambda)$ versus $a_{ph}(675)$ for high-light subtropical regimes as follows:

$$a_{ph}(\lambda) = a0 \times \exp(a1 \times tanh(a2 \times \ln(a_{ph}(675)/a3))) \times a_{ph}(675).$$

Table 2 show the NSCS regional tuning results of the Carder model for the MODIS wave bands centered at λ = 412, 443, 488, 510, 531 and 551 nm. Parameters a2 and a3 were set to the same values proposed by Carder et al. (1999).

For T-A, there appeared to be minor variation of the model parameters between the two seasons (Table 2). The lead parameter a0 was slightly higher in May 2001 than in November 2002. The largest difference between them occurred at 551 nm, corresponding to a change of ~30%. Variations of a0 at the other bands were <10%.

Differences of the model parameters between the coastal transect T-C and the shelf transects T-A and T-B in November 2002 were relatively significant (Table 2). For the three bands 412, 443 and 488 nm, the lead parameter, a0, was about 20% lower on T-C than on T-A and T-B. For 510 and 551 nm, a0 was similar along these transects.

It is thus suggested that a regional tuning (i.e., from the coastal water adjacent to the PRE to the NSCS shelf water) may be important for semi-analytical model parameterization. Tuning between the two seasons under study seems less important although a full seasonal cycle of the absorption spectral model is desirable. In addition, the parameters in this region deviated from those originally proposed in Carder et al. (1999), further demonstrating that a single parameterization is not applicable globally, and regional tuning is often required.

4 Summary

Variability of the phytoplankton absorption coefficients (α_{ph}) in the northern South China Sea (NSCS) adjacent to the Pearl River estuary (PRE) was examined based upon two cruise surveys (May 2001 and November 2002). Significant temporal and spatial variations of $\alpha_{ph}(675)$ have been found. Short-term variability in May 2001 revealed the influence of a phytoplankton bloom downstream of a large river plume induced by heavy precipitation. Seasonal differences indicated the deeper mixing in November 2002 due to the stronger winter monsoon. Because $\alpha_{ph}(675)$ is highly correlated with chl α, these variations of $\alpha_{ph}(675)$ are expected to reflect the pattern of chl α, knowledge of which is still rather limited in this region. Furthermore, variations in the absorption characteristics, such as blue/red (B/R) ratio and bathochromic shift, inferred change of phytoplankton community structure. For example, picoprocaryotes were probably an important component of the phytoplankton community on the outer shelf/slope of T-A in November, while this seemed not the case for its inner shelf portion, where the impact of Pearl River plume and coastal water was high. The results here show the potential of applying α_{ph}, a parameter relatively easy to determine, to obtain some information about the phytoplankton standing stock and community structure. In addition, fitting the measured data to the spectral model of α_{ph} of Carder et al. (1999) found greater spatial variations than seasonal variations in the model parameters, suggesting that separate models or parameters for coastal and shelf waters are

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required in order to accurately derive α_{ph} remotely for developing local semi-analytical algorithms.

The NSCS is a complex water body subject to local river plumes and coastal waters modulated by monsoon and other factors. Therefore, the limited data obtained from the two cruises are insufficient to provide the full scenario of temporal (event to non-event, seasonal) and spatial (shelf to slope) variability of α_{ph} in this water, and more intensive investigation is required. Nevertheless, our results provide for the first time a sketch of the spatial and temporal variations of α_{ph} associated with physical processes in this region.

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References

Babin, M., Stramski, D., Ferrari, G. M., Claustre, H., Bricaud, A., Obolensky, G., and Hoepffner, N.: Variations in the light absorption coefficients of phytoplankton, nonalgal particles, and dissolved organic matter in coastal waters around Europe, J. Geophys. Res., 108(C7), 3211, doi:10.1029/2001JC000882, 2003.

Bidigare, R. R., Ondrusek, M. E., Morrow, J. H., and Kiefer, D. A.: In vivo absorption properties of algal pigments, Proc. SPIE Ocean Opt. X, 1302, 290–302, 1990.

Bidigare, R. R., Smith, R. C., Baker, K. S., and Marra, J.: Oceanic primary production estimates from measurements of spectral irradiance and pigment concentrations, Global Biogeochem. Cycles, 1, 171–186, 1987.

Bricaud, A. and Stamski, D.: Spectral absorption coefficients of living phytoplankton and non-algal biogenous matter: A comparison between the Peru upwelling area and the Sargasso Sea, Limnol. Oceanogr., 35(3), 562–582, 1990.

Bukata, R. P., Jerome, J. H., Kondratyev, K. Y., and Pozdnyakov, D. V.: Optical properties and remote sensing of inland and coastal waters, CRC Press, Boca Raton, FL, 1995.

Cai, W. J. and Dai, M.: Comment on "Enhanced open ocean storage of CO2 from shelf sea pumping", Science, 306, 1477C, 2004.

Cao, W. X., Yang, Y. Z., Xu, X. Q., Huang, L. M., and Zhang, J. L.: Regional patterns of particulate spectral absorption in the Pearl River estuary, Chinese Science Bulletin, 48(21), 2344–2351, 2003.

Cao, W., Yang, Y., Liu, S., Xu, X., Yang, D., and Zhang, J.: Spectral absorption coefficients of phytoplankton in relation to chlorophyll a and remote sensing reflectance in coastal waters of southern China, Progress in Natural Science, 15(4), 342–350, 2005 (in Chinese with English abstract).

Carder, K. L., Chen, F. R., Lee, Z. P., and Hawes, S. K.: Semianalytic Moderate-Resolution Imaging Spectrometer algorithms for chlorophyll and absorption with bio-optical domains based on nitrate-depletion temperatures, J. Geophys. Res., 104, 5403–5421, 1999.

Chen, J. X., Huang, B. Q., Liu, Y., Cao, Z. R., and Hong, H. S.: Phytoplankton community structure in the transects across East China Sea and Northern South China Sea determined by analysis of HPLC photosynthetic pigment signatures, Advances in Earth Science, 21(7), 738–746, 2006 (in Chinese with English abstract).

Chisholm, S. W., Olson, R. J., Zettler, E. R., Goericke, R., Waterbury, J. B., and Welschmeyer, N. A.: A novel free-living prochlorphyte abundant in the oceanic euphotic zone, Nature, 334, 340–343, 1988.

Cleveland, J. S.: Regional models for phytoplankton absorption as a function of chlorophyll a concentration, J. Geophys. Res., 100(C7), 13 333–13 344, 1995.

Cleveland, J. S., Perry, M. J., Kiefer, D. A., and Talbot, M. C.: Maximal quantum yield of photosynthesis in the northwestern Sargasso Sea, J. Mar. Res., 47, 869–886, 1989.

Cleveland, J. S. and Weidemann, A. D.: Quantifying absorption by aquatic particles: A multiple scattering correction for glass-fiber filters, Limnol. Oceanogr., 38, 1321–1327, 1993.

Dai, M., Zhai, W., Cai, W., Callahan, J., Huang, B., Shang, S., Wang, Z., Huang, T., Li, X., Lu, Z., Chen, W., and Chen, Z.: Effects of an estuarine plume-associated bloom on the carbonate system in the lower reaches of the Pearl River estuary and the coastal zone of the northern South China Sea, Cont. Shelf Res., accepted, 2007.

Huang, B. Q., Lin, X. J., Liu, Y., Dai, M. H., Hong, H. S., and Li, W. K. K.: Ecological study of picoplankton in northern South China Sea, Chinese J. Oceanol. Limnol., 20, 22–32, 2002.

IOCCG: Remote sensing of ocean colour in coastal, and other optically-complex, waters: Report of the International Ocean Color Coordinating Group, No.3, edited by: Sathyendranath, S., IOCCG, Dartmouth, Nova Scotia Canada, 140 pp, 2000.

Kana, T. M., Glibert, P. M., Goericke, R., and Welschmeyer, N. A.: Zeaxanthin and β-carotene in Synechococcus WH7803 respond differently to irradiance, Limnol. Oceanogr., 33(6), 1623–1627, 1988.

Lau, K. M., Wu, H. T., and Yang, S.: Hydrologic processes associated with the first transition of the Asian summer monsoon : a pilot satellite study, Bull. Am. Meteorol. Soc., 79, 1871–1882, 1998.

Lazzara, L., Bricaud, A., and Claustre, H.: Spectral absorption and fluorescence excitation properties of phytoplanktonic populations at a mesotrophic and an oligotrophic site in the tropical North Atlantic (EUMELI program), Deep Sea Res. I, 43(8), 1215–1240, 1996.

Lee Chen, Y.: Spatial and seasonal variations of nitrate-based new production and primary production in the South China Sea, Deep Sea Res. I, 52, 319–340, 2005.

Lee, Z. P., Carder, K. L., and Arnone, R.: Deriving inherent optical properties from water color: a multi-band quasi-analytical algorithm for optically deep waters, Appl. Opt., 41, 5755–5772, 2002.

Lee, Z. P., Carder, K. L., Steward, R. G., Peacock, T. G., Davis, C. O., and Patch, J. S.: An empirical algorithm for light absorption by ocean water based on color, J. Geophys. Res., 103(C12), 27 967–27 978, 1998.

Li, F. Q. and Su, Y. S.: Analysis of water masses, Qingdao ocean university press, 375–385, 2001.

Liu, K. K., Chao, S. Y., Shaw, P. T., Gong, G. C., Chen, C. C., and Tang, T. Y.: Monsoon-forced chlorophyll distribution and primary production in the South China Sea: Observations and a numerical study, Deep Sea Res. I, 49, 1387–1412, 2002.

Lorenzen, C. J. and Downs, J. N.: The specific absorption coefficients of chlorophyllide a and pheophorbide a in 90% acetone, and comments on the fluorometric determination of chlorophyll and pheopigments, Limnol.Oceanogr., 31(2), 449–452, 1986.

Lohrenz, S., Weidemann, A. D., and Tuel, M.: Phytoplankton spectral absorption as influenced by community size structure and pigment composition, J. Plankton Res., 25(1), 35–61, 2003.
Lutz, V. A., Sathyendranath, S., and Head, E. J. H.: Absorption coefficient of phytoplankton: regional variations in the North Atlantic, Mar. Ecol. Prog. Ser., 135, 197–213, 1996.
Mann, K. H. and Lazier, J. R. N.: Dynamics of marine ecosystems, Blackwell Science, 389 pp, 1996.
Mitchell, B. G., Bricaud, A., Carder, K., Cleveland, J., Ferrari, G. M., Gould, R., Kahru, M., Kishino, M., Maske, H., Moisan, T., Moore, L., Nelson, N., Phinney, D., Reynolds, R. A., Sosik, H., Stramski, D., Tassan, S., Trees, C., Weidemann, A., Wieland, J. D., and Vodacek, A.: Determination of spectral absorption coefficients of particles, dissolved material and phytoplankton for discrete water samples, in Ocean Optics Protocols for Satellite Ocean Color Sensor Validation, Revision 2, edited by: Fargion, G. S., Mueller, J. L., and McClain, C. R., NASA, Goddard space flight center, Greenbelt, Maryland, 125–153, 2000.
Mitchell, B. G. and Kiefer, D. A.: Chlorophyll a specific absorption and fluorescence excitation spectra for light limited phytoplankton, Deep Sea Res., 35(5), 639–663, 1988.
Moore, L. R., Goericke, R., and Chisholm, S. W.: Comparative physiology of *Synechococcus* and *Prochlorococcus*: influence of light and temperature on growth, pigments, fluorescence and absorptive properties, Mar. Ecol. Prog. Ser., 116, 259–275, 1995.
Morel, A., Antoine, D., Babin, M., and Dandonneau, Y.: Measured and modeled primary production in the northeast Atlantic (EUMELI JOGFS program): the impact of natural variations in the photosynthetic parameters on model predictive skill, Deep Sea Res. I, 43(8), 1273–1304, 1996.
Ning, X., Chai, F., Xue, H., Cai, Y., Liu, C., and Shi, J.: Physical-biological oceanographic coupling influencing phytoplankton and primary production in the South China Sea, J. Geophys. Res., 109, C10005, doi:10.1029/2004JC002365, 2004.
Ning, X. R., Cai, Y. M., Li, G. W., and Shi, J. X.: Photosynthetic picoplankton in the northern South China Sea, Acta Oceanologica Sinica, 25(3), 83–97, 2003 (in Chinese with English abstract).
Partensky, F., Hoepffner, N., Li, W. K. W., Ulloa, O., and Vaulot, D.: Photoacclimation of *Prochlorococcus sp.* (Prochlorophyta) strains isolated from North Atlantic and the Mediterranean Sea, Plant Physiol., 101, 285–296, 1993.
Preisendorfer, R. W.: Application of radiative transfer theory to light measurements in the sea, International Union of Geodesy and Geophysics, 11–30, 1961.

Prieur, L. and Sathyendranath, S.: An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials, Limnol. Oceanogr., 26, 671–689, 1981.
Qian, W. H., Zhu, Y. F., Kang, H. S, and Lee, D. K.: Temporal-spatial distribution of seasonal rainfall and circulation in the East Asian monsoon region, Theoretical and Applied Climatology, 73, 151–168, 2002.
Sosik, H. M. and Mitchell, B. G.: Absorption, fluorescence and quantum yield for growth in nitrogen-limited Dunaliella tertiolecta, Limnol. Oceanogr., 36, 910–921, 1991.
Stramski, D. and Morel, A.: Optical properties of photosynthetic picoplankton in different physiological states as affected by growth irradiance. Deep Sea Res., 37, 245–266, 1990.
Stuart, V., Sathyendranath, S., Platt, T., Maass, H., and Irwin, B.: Pigments and species composition of natural phytoplankton populations: effect on the absorption spectra, J. Plankton Res., 20, 187–217, 1998.
Su, J.: Overview of the South China Sea circulation and its influence on the coastal physical oceanography outside the Pearl River Estuary, Cont. Shelf Res., 24, 1745–1760, 2004.
Tseng, C. M., Wong, G. T. F., Lin, I. I., Wu, C. R., and Liu, K. K.: A unique seasonal pattern in phytoplankton biomass in low-latitude waters in the South China Sea, Geophys. Res. Lett., 32, L08608, doi:10.1029/2004GL022111, 2005.
Wang, G. F., Cao, W. X., Xu, D. Z., Liu, S., and Zhang, J. L.: Variations in specific absorption coefficients of phytoplankton in northern South China Sea, J. tropical Oceanogr., 24(5), 1–10, 2005 (in Chinese with English abstract).
Xu, X. Q., Cao, W. X., and Yang, Y. Z.: Relationships between spectral absorption coefficient of particulates and salinity and chlorophyll a concentration in Zhujiang river mouth, J. Tropical Oceanogr., 23(5), 63–71, 2004(in Chinese with English abstract).
Zhai, W. D., Dai, M. H., Cai, W. J., Wang, Y. C., and Hong, H. S.: The partial pressure of carbon dioxide and air–sea fluxes in the northern South China Sea in spring, summer and autumn, Mar. Chem., 96, 87–97, 2005.
Zhu, G., Ning, N., Cai, Y., Liu, Z., and Liu, Z.: Studies on species composition and abundance distribution of phytoplankton in the South China Sea, Acta Oceanologica Sinica, 25(supp.2), 8–23, 2003 (in Chinese with English abstract).

Table 1. B/R ratios ($\alpha_{ph}(440)/\alpha_{ph}(675)$) in the Northern South China Sea in May 2001 and November 2002.

	2001-5				2002-11			
station	depth(m)	B/R ratio	station	depth(m)	B/R ratio	station	depth(m)	B/R ratio
3	1	3.4	3A	1	3.4	C1	1	2.6
3	37	2.6	3A	40	2.9	C1	5	2.9
3	50	2.6	3A	80	2.3	C1	39	2.2
3	75	3.8	3A	110	2.4	C2	1	2.8
2	1	3.4	3	1	3.2	C2	10	2.6
2	10	3.1	3	10	3.5	C2	35	2.1
2	30	2.3	3	50	2.8	C3	1	2.1
2	60	2.5	3	100	2.1	C3	7	2.3
2	100	3.4	3	120	2.3	C3	31	2.2
4A	1	3.6	4	1	3.1	C4	1	2.3
4A	20	3.8	4	20	3.0	C4	10	2.3
4A	40	2.3	4	80	2.3	C4	20	2.2
4A	100	3.6	2	1	2.6	C4	42	1.9
5A	1	3.3	2	10	2.6	C5	1	2.0
5A	10	3.1	2	50	2.7	C5	40	2.3
5A	40	2.7	2	75	2.3	B1	1	3.7
5A	50	2.6	2	100	2.5	B1	20	3.4
5A	70	2.3	4A	1	3.1	B1	40	2.5
5A	85	2.5	4A	10	2.9	B1	70	2.5
6	1	3.9	4A	40	2.9	B1	120	2.7
6	10	3.4	5	1	2.7	B2	1	3.5
6	20	3.9	5	15	3.1	B2	20	2.2
6	33	3.2	5	30	3.2	B2	50	2.9
6	45	2.6	5	45	2.5	B2	80	3.6
6	60	2.5	5	60	2.0	B2	100	2.4
6	66	2.4	5	80	3.0	B2	140	2.2
2’	1	3.2	5	100	2.9	B3	1	3.5
2’	10	3.4	5A	1	2.4	B3	10	3.3
2’	37	3.2	5A	5	2.5	B3	60	2.5
2’	75	2.3	5A	10	2.4	B3	80	2.4
2’	100	2.7	5A	25	2.2	B3	100	3.3
6’	1	2.5	5A	50	2.3	B4	1	3.5
6’	5	2.6	5A	84	2.4	B4	20	3.0
6’	20	2.6	6	1	2.5	B4	50	2.2
6’	50	2.4	6	15	2.4	B4	80	3.8
6’	65	2.5	6	25	2.6	B5	1	3.4
6C	1	2.1	6	35	2.6	B5	60	2.4
6C	45	2.3	6	65	2.3			

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Table 2. Parameters of the phytoplankton absorption spectral model.

Wavelength (nm)	parameters	May-2001 T-A	Nov-2002 T-A	Nov-2002 T-B	Nov-2002 T-C	Carder et al (1999)
	a0	2.00	1.85	1.94	1.53	2.2
	a1	0.45	0.29	0.55	–0.21	0.75
412	a2	–0.5	–0.5	–0.5	–0.5	–0.5
	a3	0.0112	0.0112	0.0112	0.0112	0.0112
	R^2	0.96	0.90	0.89	0.78	\
	a0	2.39	2.38	2.53	1.96	3.59
	a1	0.49	0.26	0.29	0.26	0.8
443	a2	–0.5	–0.5	–0.5	–0.5	–0.5
	a3	0.0112	0.0112	0.0112	0.0112	0.0112
	R^2	0.99	0.94	0.92	0.66	\
	a0	1.73	1.62	1.78	1.39	2.27
	a1	0.36	0.27	0.35	0.27	0.59
488	a2	–0.5	–0.5	–0.5	–0.5	–0.5
	a3	0.0112	0.0112	0.0112	0.0112	0.0112
	R^2	0.99	0.97	0.97	0.77	\
	a0	1.02	0.89	0.96	0.86	1.4
	a1	0.33	0.32	0.51	-0.43	0.35
510	a2	–0.5	–0.5	–0.5	–0.5	–0.5
	a3	0.0112	0.0112	0.0112	0.0112	0.0112
	R^2	0.97	0.92	0.93	0.94	\
	a0	0.38	0.30	0.34	0.33	0.42
	a1	–0.66	0.06	0.39	–1.88	–0.22
551	a2	–0.5	–0.5	–0.5	–0.5	–0.5
	a3	0.0112	0.0112	0.0112	0.0112	0.0112
	R^2	0.87	0.68	0.64	0.87	\

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Phytoplankton absorption coefficients in the northern SCS

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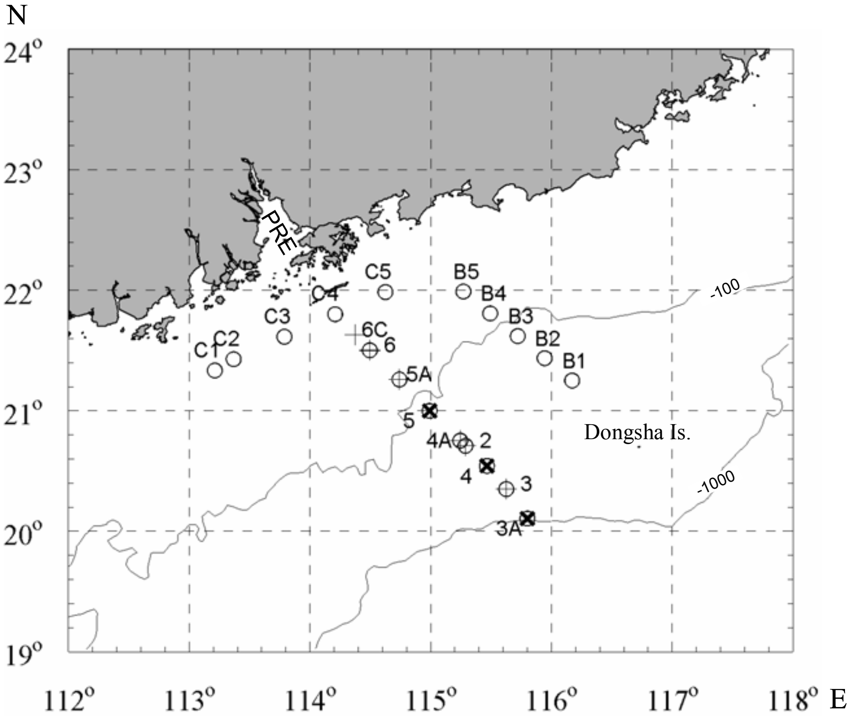

Fig. 1. CTD and sampling stations in the northern South China Sea. +: CTD and sampling stations in May 2001; ×: stations only for CTD in May 2001; ○: CTD and sampling stations in November 2002; PRE: the Pearl River Estuary; Dongsha Is.: Dongsha island.

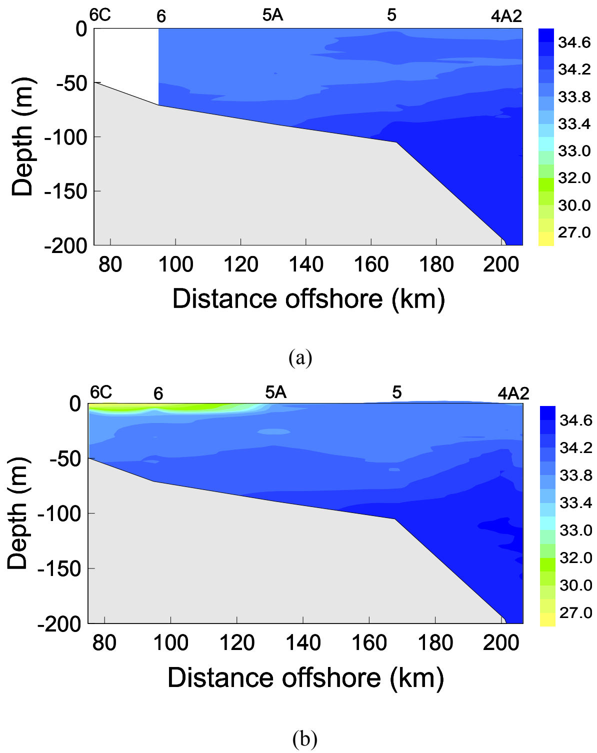

Fig. 2. Changes of salinity between the two cruise legs. **(a)** 14–19 May; **(b)** 24–25 May.

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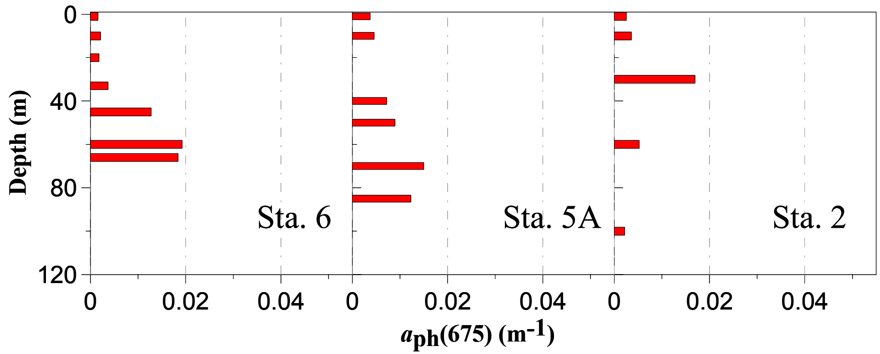

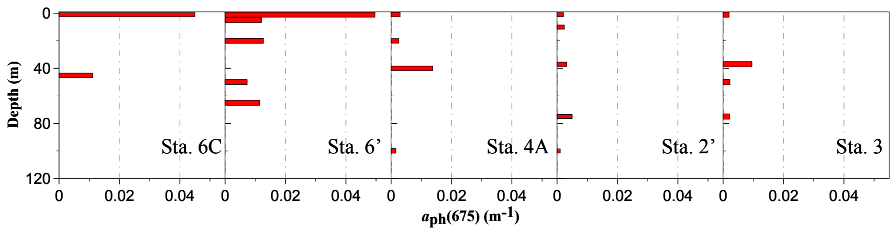

Fig. 3. Vertical distribution of $\alpha_{ph}(675)$ during the two cruise legs in May 2001. **(a)** 14–19 May; **(b)** 24–25 May.

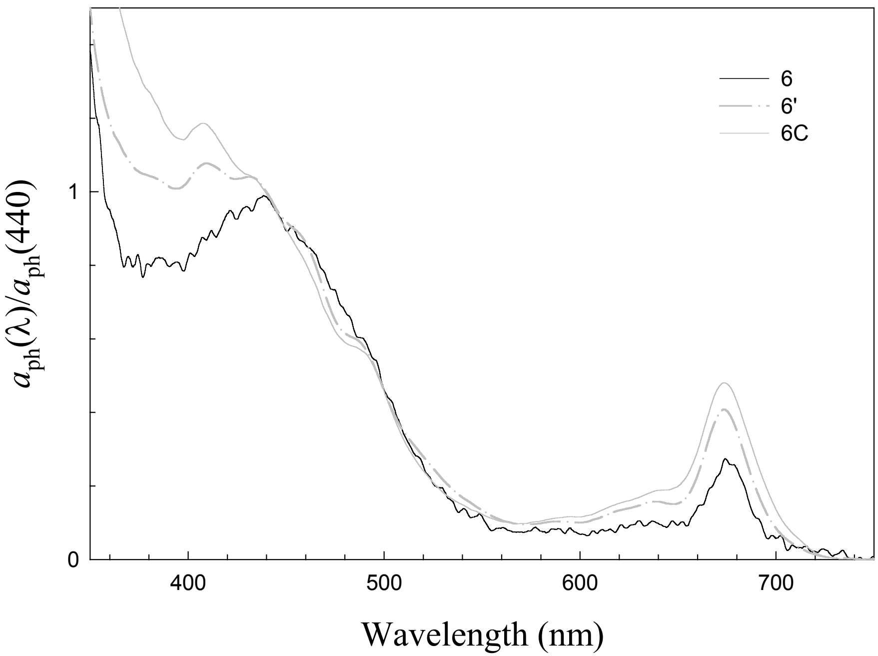

Fig. 4. Surface α_{ph} normalized at 440 nm at Sta. 6 and Sta. 6C. Sta. 6C was sampled during the second cruise leg when Sta. 6 was revisited (annotated as Sta. 6').

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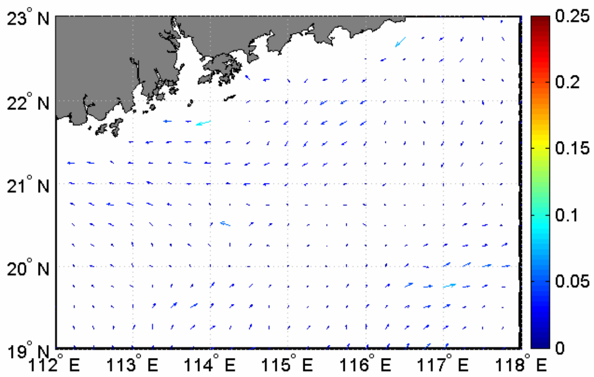
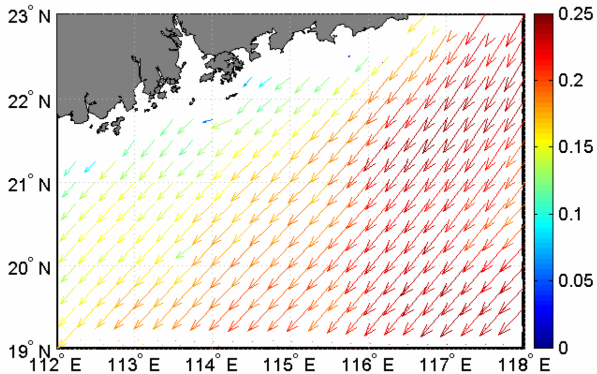


(a)



(b)

Fig. 5. Monthly mean wind stress as observed by QuikSCAT during May 2001 **(a)** and November 2002 **(b)**. The unit is $N\,m^{-2}$.

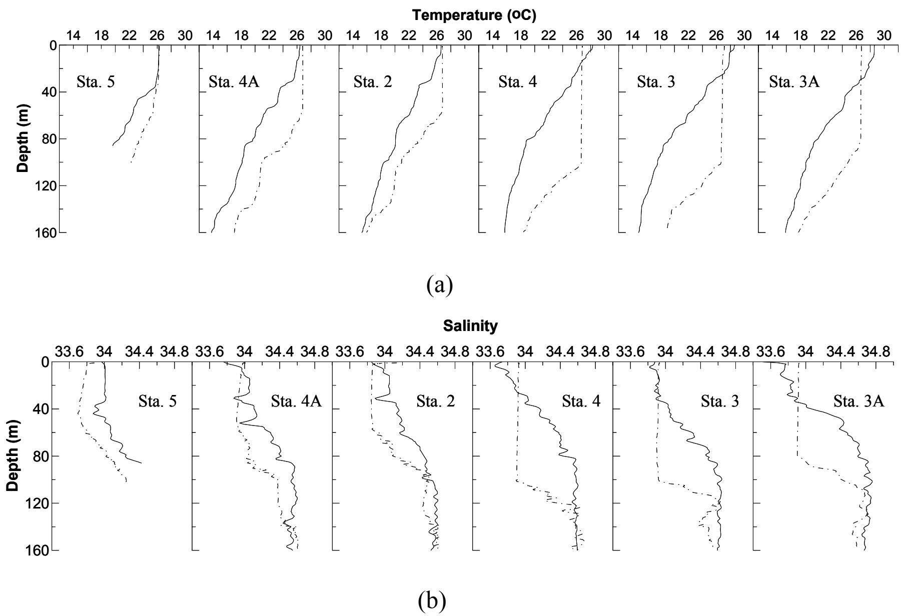


Fig. 6. Temperature **(a)** and salinity **(b)** profiles on the outer shelf/slope of transect A. The solid and dash lines represent observations in May 2001 and November 2002, respectively.

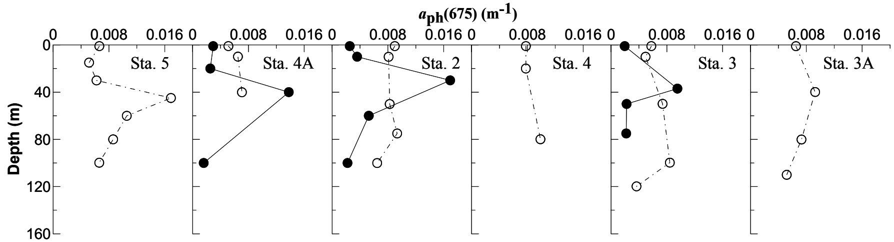
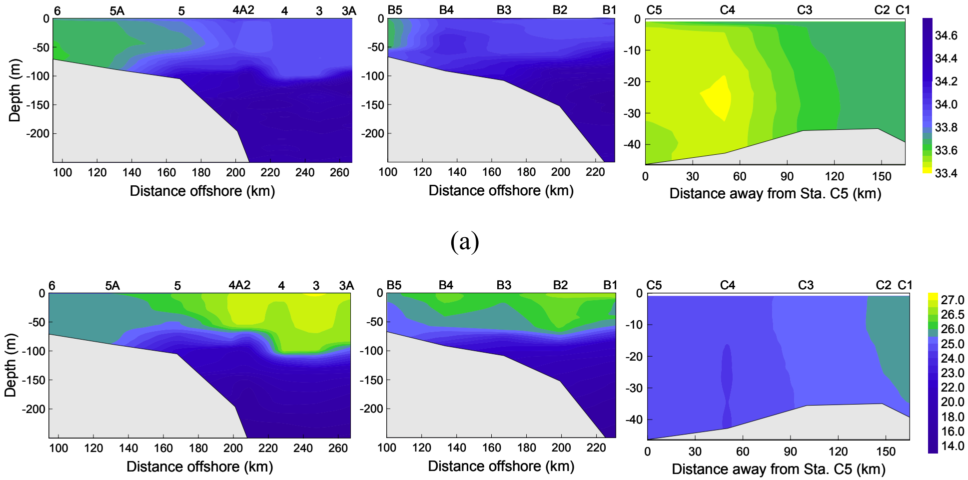


Fig. 7. Vertical distribution of $\alpha_{ph}(675)$ on the outer shelf/slope of transect A. Observations in May 2001 and November 2002 are represented with bold and open circles respectively.



(a)

(b)

Fig. 8. Salinity **(a)** and temperature **(b)** distribution on Transect-A, B and C (from left to right) in November 2002.

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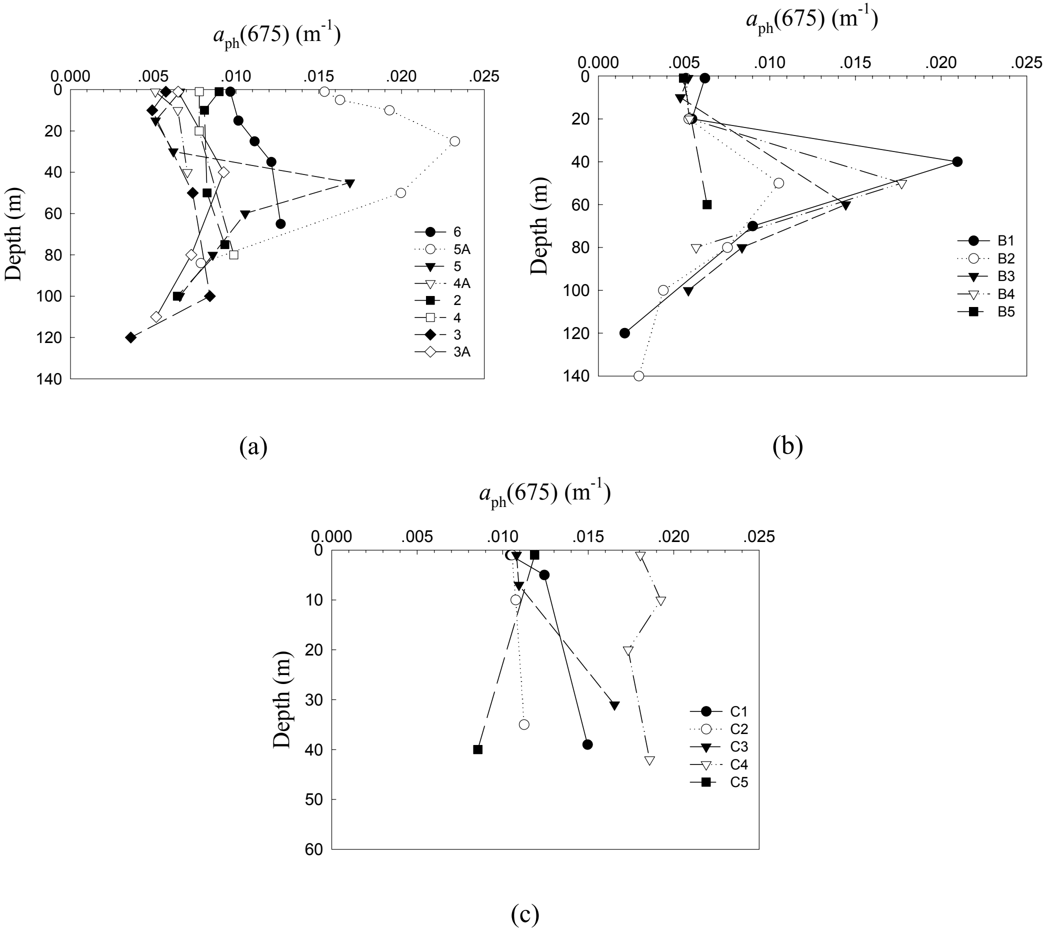

Fig. 9. Vertical profiles of $\alpha_{ph}(675)$ in November 2002 on T-A **(a)**, T-B **(b)** and T-C **(c)**.

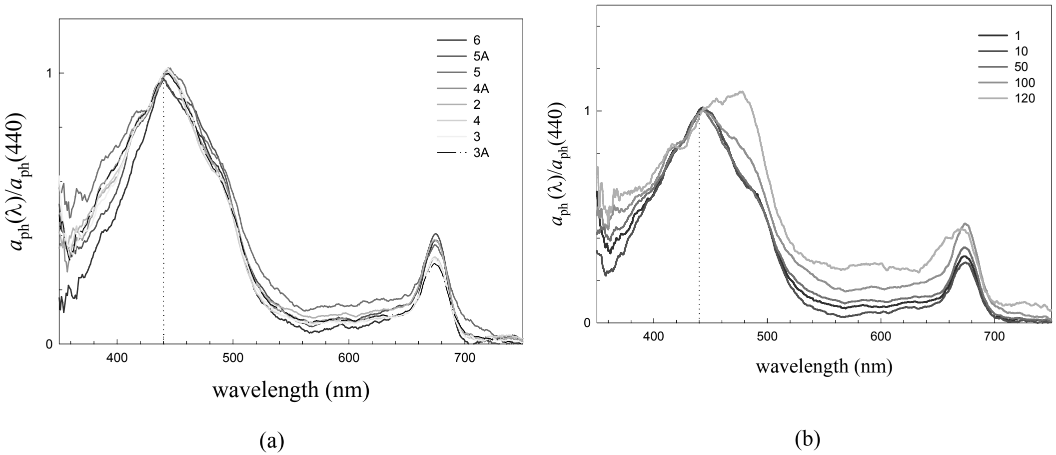

Fig. 10. α_{ph} normalized at 440 nm in November 2002. **(a)** Surface distribution on Transect A; **(b)** Vertical distribution at Sta. 3. The legend in (b) shows the sampling depths in meters. The dotted vertical line in the graphs highlights the normal absorption peak at 440 nm.